AN INTERIM REPORT ON A SET OF PROPOSED GUIDELINES FOR PEDESTRIAN LEVEL WIND STUDIES FOR BOSTON MASSACHUSETTS

by

Frank H. Durgin

WBWT-TR-1214 January 1985

Submitted to

Boston Redevelopment Authority
1 City Hall Square
Boston, Massachusetts 02201

Wright Brothers Facility
Department of Aeronautics and Astronautics
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I INTRODUCTION

In 1948 the tallest building in Boston was the Custom House Tower. During the past 36 years, starting with the construction of the original 26 story John Hancock tower on Berkeley Street, Boston has seen the construction of about 50 buildings 25 stories or taller. This new construction has resulted in the rebuilding of most of the downtown and business areas, the Copley Square area, and now the waterfront areas. While the net effect of this building spree has been a rejuvenation of Boston, there has been one negative aspect; namely, that in certain areas the new buildings have resulted in excessively strong and uncomfortable pedestrian level winds.

Over the years, in recognition of this problem, the Boston Redevelopment Authority (BRA) has required that for each project of a certain size or greater, a study be made of the possible effects of any proposed building on pedestrian level winds in its vicinity. Such studies can be as simple as a report from a qualified consultant giving his estimates of the winds at the base of the building. Such estimates can only be qualitative. Other studies have included a wind tunnel test to measure the effect of the new building on the wind environment. Typically such testing has been required for any building 25 stories or taller. Under what conditions such tests should be required is one of the issues that will be addressed in this report.

Wind tunnel studies of pedestrian level winds involve several steps and decisions: 1) Simulating the approach flow; 2) Modeling the city for a sufficient area around the proposed building such that all buildings and objects which might affect the flow around the building are modeled; 3) Choosing the appropriate stations at which to make the measurements; 4) Measuring the pedestrian level wind velocity at each station; 5) Obtaining a valid statistical description of the Boston wind climate that can be combined with measured wind velocities from the wind tunnel so as to predict how often a given average wind or gust will occur either annually and/or seasonally; and finally, 6) Finding a criteria for the results that accounts for various types of pedestrian activity.

While the literature [1,9,14,38,and 39] includes descriptions of methods for carrying out each of the above six steps that would be a part of any wind tunnel study of pedestrian level winds, more than one method of accomplishing each is available. Further, the state of the art for completing most of the steps allows sufficient latitude in setting up and carrying out any study that, in general, the BRA has not found it possible to directly compare the results from two different wind tunnels. A major objective of this study is to combine a brief review of the literature and the author's wind tunnel experience to suggest ways to make the results from any two wind tunnel tests more comparable. One obvious way of accomplishing that objective is to eliminate most of the variation in the way the several steps are carried out. If that can be accomplished, it should then be possible to set up a city-wide program to check the validity of the results and thus of the overall methodology.

Section II of this report will discuss the situations for which a wind tunnel test should be reqiured. Sections III - VIII deal with the six steps outlined above. Section IX suggests methods of checking the validity of the results, and Section X summarizes the results of the study.

It should be borne in mind that this report is intended as a preliminary study based primarily on the author's experience. The literature cited is therefore limited. A more complete literature survey is advisable before implementing many of the suggested procedures other than on a temporary basis.

II WHEN SHOULD A WIND TUNNEL STUDY OF PEDESTRIAN LEVEL WINDS BE CARRIED OUT

It is not unusual for a developer and/or architect to hire a qualified consultant to evaluate the potential windiness at the base of a proposed building. Such an evaluation, of necessity, is qualitative, but still can be very usefull because the consultant can, and frequently does identify potential problem areas. The evaluation should also provide the kinds of information needed to decide whether or not a wind tunnel test would be useful. There is, however, no way known to the author to make such a study quantitative except for some very special cases.

It is difficult if not impossible to set up a criteria for when a pedestrian level wind tunnel study is needed. The difficulty arises out of the same need which leads to the use of a wind tunnel for such studies. That is ,the wind-city interaction is so complex, that at least to date, no one has developed an accurate analytical approach to the problem. Further even persons with considerable experience are not always able to even predict which way the wind will blow at ground level in certain situations.

Thus, it does not seem possible to set up a specific height criteria for when a wind tunnel study of pedestrian level winds should be carried out. To further illustrate the point, Figure 1 is a photograph of three identical buildings in Indianapolis, Indiana at which the author installed some instruments in the far left building. The main entrance to the complex is in the concrete wall in that far left building. Several times during visits to the buildings, that entrance had to be roped off because of the wind. These buildings were only 11 stories (110 ft) high. Alternately, it is relatively clear that a forty story building placed in an open space in the middle of 10 to 15 fifty story buildings is unlikely to adversely affect the winds at its base or near the base of any of the 50 story buildings. In fact it is likely to reduce the winds in both areas.

In the next section of this report and in Appendix I it is shown that the velocity of the natural wind increases with height; the more open the area the more rapid that increase. When one erects a building one creates the possibility that the faster winds at the top of the building can be brought down to ground level. Thus, the tendency is to think that the taller the building the more likely that the winds at its base will be adversely affected. In general that is true, but not always as illustrated above.

The point is that it is not the absolute height, but

rather the relative height with respect to its immediately surrounding buildings that determines whether or not a building is apt to adversely affect the winds at its base. As can be seen in Figure 1, the 11 story buildings in Indianapolis are set in the open far from any other buildings, so that they are very high with respect to their surroundings. Further, because they are situated in a very open area, the average wind velocity can be expected to increase relatively rapidly with height.

An important question then becomes how to define what is meant by relative height, and to indicate other factors that might be important. First one can say that any building 10 stories or higher that is twice as high as its adjacent buildings is a good candidate for a test. In this case, adjacent would also apply to a building across the street as well as in the same block. An interesting point is that a building as little as 1.5 times the height of adjacent buildings along a wide street such as Commonwealth Avenue in Back Bay would probably increase the winds along the sidewalks for new as well as nearby older buildings. This same effect showed up for the building at 151 Tremont Street in a study of Lafayette Square carried out at Wright Brothers Facility (WBF) [15]. There are many special cases such as buildings with open passageways through them at the base, or buildings open at the bottom that can, and frequently do, lead to adverse winds.

III MODELING THE APPROACH FLOW

In 1967, Van Der Hoven [40] published an article in the Journal of Meteorology entitled "Power Spectrum of Horizontal Wind Speeds in the Frequency Range 0.0007 to 900 Cycles per Hour." His spectrum is given in Figure 2. The spectrum is a plot of the relative energy of the wind at Brookhaven, N.Y. as a function of frequency and is based on three years of continuously recorded data. Note the peaks at 100 hrs, 12 hrs and 1 minute. It is the presence of the "spectral gap" (very little energy) between 6 hours and 10 minutes that allows us to separate the winds into the macrometeorological and micrometeorological ranges shown, and thus makes the use of wind tunnels for quantitative investigations of wind effects on buildings and cities possible. For convenience the separation point between the two ranges is usually made at 1 hour, although actually, any time from 2 hours to 20 minutes could probably be used.

In the macrometeorological range of the spectrum, the winds are usually described statistically. That is, one determines the probability of a given average hourly wind at gradient height occurring as a function of time and direction. How that is done and the problems associated with the processes are described in Section VII.

The micrometeorological range of the spectrum is simulated in the wind tunnel and is referred to as the approach flow. Further, because of the assumed one hour separation point, it is generally assumed the gradient velocity in the wind tunnel is equivalent to an hourly average wind at gradient height full scale [1, 14, 38, 39].

In reality the approach flow (also called the earth's boundary layer flow) to any site from any direction is highly variable. Its characteristics are dependent not only on the general upstream roughness and all very large objects upstream (including hills, valleys etc.), but also the type of storm or other phenomena creating the wind and the relative thermal equilibrium of the flow. However, a number of comparisons of measured and wind tunnel generated wind rose data has shown that one can neglect all but the upstream roughness including large scale roughness for studies where one is interested only in an overall estimate of the occurrence of pedestrian level winds as is the case here (see Murakami et al [31]). Thus it is common practice to simulate only the thermally neutral earth's boundary layer in the wind tunnel for the approach flow.

There are two basic methods of simulating the earth's boundary layer in a wind tunnel: 1) using a long test section

with appropriate roughness over the entire length of the floor in order to generate the boundary layer more or less naturally; and 2) using vortex generators, spires, blowing, or some other technique to generate the boundary layer artificially in a short test section wind tunnel [19,39]. In fact all kinds of combinations of the above two methods are used. However, it is the resulting simulated earth's boundary layer, and not the exact method used to create it that is important.

There are also two methods of checking the validity of any given simulated Earth's boundary layer. The first and more theoretically sound approach uses the so-called "law of the wall," which in turn leads to the assumption of a logarithmic velocity profile. For this approach it is assumed that one has a true boundary layer with the known relationships between shear, turbulence intensity, gust size, and surface roughness of a neutrally stable boundary layer. This is a valid assumption for a naturally developed boundary layer, but is not necessarily so for an artificially generated boundary layer. For that reason, the author favors use of the second more empirical approach suggested by Davenport and Isyumov [7], in which the variation of average velocity and longtitudinal turbulence intensity versus height as well as the power spectrum of the longitudinal turbulence for the scaled boundary layer is matched with typical data measured full scale.

Matching the variation of average velocity with height assures that average flow over the city and more specifically near the building of interest will be the same as exists in full scale. Matching the turbulence intensity assures that the total energy in the gusting flow is correct. Matching the power spectral density assures that the distribution of gust sizes with respect to building size is the same as full scale. Matching these three parameters ensures that the overall characteristics of the flow are matched, and so is generally accepted as adequate for pedestrian level wind studies.

One could, of course, try to also match the intensities of the vertical and lateral components of the gusting as well as their spectra and cross correlation coefficients. However, it is not usually known what the effects of nonthermal equilibrium or upstream hills and valleys are on the full scale flow. Thus, it is not clear what the matching should be, and it is not usually attempted.

An example of a matching of the three major boundary layer parameters as given in a typical report from the Wright Brothers Facility (WBF) is presented in Figure 3a, b, and c and described in Appendix I. Typically for Boston the height of the boundary layer should be between the equivalent of 1100 and 1300 feet full scale and the power law exponent betweem 0.22 and 0.28. The power spectrum should indicate a match within a factor of two (that is the peak in the power spectrum should be

within 0.3 of the proper value on a base 10 Logarithmic scale). Since it is difficult to simulate the larger scale gusts in a wind tunnel, typically the tunnel spectrum will lie somewhat to the right of the Davenport empirical and/or the von Karman spectra shown in Figure 3c. Alternatively, to obtain a good fit the length used in the Davenport spectrum can be made less than the 4000 feet suggested by Davenport (but not less than 2000 feet).

IV MODEL SCALE AND THE NECESSARY AREA MODEL

The scale of the model should be determined by the scale of the simulated boundary layer. Typical scales used for studies of pedestrian level winds vary from 1-300 to 1-600. Assuming a typical size wind tunnel with an eight foot diameter turntable, only scales from 1-400 to 1-600 are reasonable for Boston because of the many 25-60 story buildings and the necessity to model the city around any building for at least a 1500 feet radius. Of course, a larger tunnel with a larger turntable (say 12 ft) would allow the use of a scale of 1-300. The importance of this requirement is illustrated by the fact that the winds at the base of either the John Hancock Tower or the Prudential Tower in Boston are affected by the other building when the wind comes from the direction of the other tower despite the fact that the towers are over 2000 feet apart.

Of course a smaller buildings which are not significantly larger than typical buildings in the city will create turbulence of the scale of the general turbulence and would not have such an effect. In any case it is important that all buildings which are in close proximity to the building of interest be modeled quite accurately. The accuracy of the modeling becomes less important as one moves away from the building of interest.

Many architects and planners do not have sufficient appreciation of this fact, and it is not uncommon to discover buildings missing from the plans and maps supplied to WBF. A possible remedy would be to require that several photographs of the area model be included in the report describing the study and its results. Examination of such photographs by the BRA would allow a determination whether or not any significant buildings had been omitted. After the results of a few tests have been questioned as a result of left out buildings, the developers, architects, and wind tunnel operators all will tend to be much more careful.

V FLOW VISUALIZATION AND THE CHOICE OF MEASURING STATIONS

The choice of the number and location of stations is fundamental to obtaining the necessary test information. Ideally a very large number of stations would ensure that all windy areas are located. Unfortunately the cost of such studies increases with the number of stations, and thus there is a tendency to test a minimum of stations. The Copley Place study [20] in which only 21 stations were used for two hotels and a large office building is an extreme example of this tendency. At least 50 and possibly up to 100 stations would have been desirable for such a large project.

The choice of stations should involve several considerations: 1) Stations should be assigned at all exits and entrances to the building or complex and at the entrances of nearby buildings where the winds might be affected by the proposed project; 2) Stations should be chosen to cover all sidewalks, passageways, and other areas nearby where pedestrian traffic is expected and that may be affected by the proposed building; 3) Stations should cover all expected street crossing places. This aspect of the problem is frequently forgotten. In fact, currently there are at least two places in Boston where it is unsafe for frail people to cross the street without help on certain windy days. 4) Special attention should be given to those areas where pedestrians are expected to remain stationary for either short or long periods of time (this includes parks, window shopping areas, sidewalk cafes, etc.); And finally, 5) at least a few stations should be placed in some well chosen spots in the city specified by the BRA (Such stations should be scattered throughout the city in such a way that at least 4 or 5 would fall within an area model needed for the wind tunnel test of any future building). These same stations could eventually be used for obtaining full scale data in the city and thus would be useful for evaluating the validity of the wind tunnel results. The exact location of these stations is probably something that should be based on the experience of people familiar with the area in which each station falls.

If actual testing included all the possible stations suggested above one would find that 50-100 stations would be needed for almost any building. Such a test would be relatively expensive. As a result, a preliminary qualitative test is frequently run in which the flow is visualized to allow one to choose and test only the most critical stations where some windiness is expected. Currently there are two approaches to this type of test. The use of; 1) smoke to directly visualize the flow, and 2) the erosion of small particles to indicate the location of windy areas. The use of smoke provides a good method of examining the basic flow patterns;

but all judgments of relative wind speed only can be done very qualitatively. The use of the erosion of small particles allows one to examine all areas at once (everywhere one spreads the particles) and by increasing the wind tunnel speed in small steps to evaluate the relative windiness everywhere. The author has used the erosion method to evaluate the windiness of large areas and/or sections of cities [10, 12, 13, 15, 16, 17, 18, 32, and 37]. The photographs from an erosion study can be used to estimate the peak velocity at any point in the area covered by the particles. One can use those estimated peak velocities in the same way one uses the measured peak velocities from a hot wire or other methods that accurately measure pedestrian level velocities. The primary shortcomings of this technique are that it only obtains data at discrete velocities, and that the particles sense the peak velocity at about the top of the particles which is below pedestrian level [21]. Nevertheless, the erosion technique does provide an excellent method of quickly and efficiently finding all windy areas.

It appears that an optimum way to perform a pedestrian level wind study is to first perform an erosion study to determine all windy locations (i.e. taking the necessary photographs, but only analyzing them qualitatively to find the windy areas), and second to use those results to select the stations for the more quantitative hot wire study. Use of this technique ensures that one does not miss a windy station, while at the same time allows the use of a minimum number of stations for the more expensive quantative study.

VI MEASUREMENT OF PEDESTRIAN LEVEL WINDS IN A WIND TUNNEL

Fundamental to the taking of pedestrian level wind data in the wind tunnel is the assumption that the ratio of any velocity (average, rms, or peak) measured at pedestrian level to gradient velocity is independent of the gradient velocity. Thus one needs only to measure the ratio at one gradient velocity and to know the behavior at all gradient velocities.

There are many ways to measure the wind velocities at pedestrian level in a wind tunnel test of a building. The two most common use either a hot wire or hot film sensor. In these, the hot wire or hot film is maintained at a constant hot temperature and the electrical current required to maintain that hot temperature is monitored. Because the instruments are small and the electronics used to control the temperature (current) have high gain, both will respond to the gusting flow and allow measurement of the dynamic variation of the wind velocity. A third way of measuring these pedestrian level velocities involves the use of a special two hole probe and two pressure sensors. This method was developed by Peter Irwin while he was at the National Research Council in Canada [25]. It is not clear that his method is as accurate as the previous two. Other methods have been used, but currently only these three appear to be sufficiently accurate, reliable, and have the necessary frequency response for the required measurements.

It is important to point out that all three of these methods of measurement suffer at least one basic flaw; they are insensitive to the wind's direction. Thus, when there is sufficient turbulence (greater than about 20%) that the flow sometimes reverses, these devices rectify the reversed flow causing the average velocity to be too high and the root mean square variation about the average to be too low, but with no error in the peak velocity [23]. When a three cup anemometer is used to measure the full scale velocities on site it will behave in the same way, in which case, the wind tunnel and on site measured velocities would be directly comparable even if they are not perfectly accurate.

While in most cases it is the average wind that will make a station windy, that is not always the case. In a few instances one finds it is the unexpected sharp gust or sometimes just the fact that the station is gusty that makes it seem windy. It is these possibilities that make it necessary to measure not only the average, but also the rms and peak wind velocities at each station. It also explains the necessity to make the measurements with an instrument that will respond to the dynamic changes in velocity as noted above.

There are two factors involving time that should be

considered when taking pedestrian level wind data in a wind tunnel. Of course, one must sample long enough to obtain a repeatable average and rms. But, longer samples imply larger measured peaks (because of the random nature of the peaks). Thus one must establish a time relationship between the wind tunnel and full scale situation. As pointed out in Section III the wind tunnel is considered to be simulating one hour of full scale wind. Thus the question becomes what time in the wind tunnel is the equivalent of one hour full scale?

This is not a simple question, since wind tunnel data is usually taken at one gradient velocity. The nondimensional time ("similarity parameter"), which must be the same in the wind tunnel as for full scale is ((velocity x sample time)/dimension). The desired final result is a calculation of the probability of any velocity occurring at each ground station. But the "similarity" relation above implies that to obtain the probability of a low velocity occurring, a short sampling time should be used, and to calculate the probability of a higher velocity, a longer one.

Typically the judgment of the windiness is based on the 1 or 2 percent occurrence velocity. Since the ratios of the full scale velocity at pedestrian level to gradient height are the same for all velocities, the 1 or 2 percent occurrence full scale gradient velocity is used in the calculation of the full scale "similarity parameter", and tunnel gradient velocity for the calculation of it in the wind tunnel at WBF. Note that only the estimates of the peak velocity probability and, not the average or rms will be in error. Further the error is conservative (i.e. for a given probability the calculated peak velocity will be too high). A sample of the use of this "similarity parameter" is included in Appendix I.

The second timing factor that must be considered when actually taking pedestrian level wind data in the wind tunnel, results from the fact that Murakami et al [30] and Hunt et al [24] have all shown that gusts lasting less than 2 or 3 seconds do not seriously affect people. Thus it is important to filter out of the wind tunnel data all gusts shorter than the equivalent of 2 or 3 seconds full scale. The same "similarity parameter" as is used above is applicable and leads to the similar problems; that is, a separate filter should be used for each velocity and use of a single filter based on the 1 or 2 percent occurrence velocity results in a lower cutoff frequency than one based on a lower more frequently occurring velocity. Thus in this case, use of the higher velocity in the "similarity paremeter" tends to be nonconservative. That is, it results in a filter that cuts off more energy than one based on a lower velocity. Use of such a filter will lead to the correct values of estimated velocity for the 1 or 2 percent occurrence velocity, and for that reason it is used at WBF. A sample of this calculation is given in Appendix I. Use of such

a filter will reduce both the measured rms and peak velocities by up to 10 or 20 percent. Thus it is very important to be sure that all data from every tunnel is filtered in the same way. That is, the effective frequency response of the measuring system used in each wind tunnel must be the same relative to the "similarity parameter," otherwise comparisons of the occurrence of effective gusts and peak gusts will not be comparable between different wind tunnels.

VII DEFINING THE BOSTON WIND CLIMATE

From the wind tunnel operator's point of view, defining the wind climate is one of the most uncertain parts of the process of estimating pedestrian level winds. While every operator must obtain the necessary data from the National Climatic Center in Ashville N.C., several different sets of data (from both surface and balloon type measurements) are available. Further, there are different methods of using each set, which, even in a given laboratory, will change with time as the personnel learn or develop better ways of analyzing the data available.

Figure 4 has been included to illustrate the problem. Shown in the figure are two sets of wind roses for Boston in which the percent of the time the wind blows from each of the sixteen compass directions is indicated by the length of the line in that direction from the center of the figure. Note the raw data is shown so that the differences are real and contained in the data base. The wind rose on the left compares three sets of surface data: one using data from Logan Airport for the years 1945 to 1965 that contains 176000 observations; a second set of data from Logan for the years 1965 to 1975 that contains 28000 observations; and a third set taken from the winds aloft data taken at ground level that contains only 4800 observations. The large differences in numbers of observations is partially due to the fact that after 1965 observations at Logan were made at three hour intervals instead of every hour as had been done previously. Winds aloft data is taken twice daily.

The wind rose on the right in Figure 4 compares two sets of winds aloft data taken at a height of 500 meters: One is a composite of data taken at Chatham Ma., Nantucket Ma., Portland Me., and Albany N.Y., where the data from each station has been weighted with respect to the inverse of the station's distance from Boston and the total data base contains 44000 observations; and the second is from the same eight years of winds aloft data shown in the left hand figure, but is taken at 500 meters not sea level.

Clearly there are significant differences between the five sets of data. Some of the differences are probably due to the different sizes of the data bases, but most are probably due to the different methods of taking the data and in the case of the surface data on the left, the fact that the winds at the anemometer at the airport are affected by the changes in buildings at the airport as well as in the city which is only a mile or so away. Of course the position of the anemometer as well as its height have also changed. The winds aloft data is probably the more reliable of the two sets, but it suffers from

lack of observations as well as the fact that there is a tendency to launch the balloons in a relatively calm period. Thus it probably has a bias toward lower velocity winds.

The comparisons shown in Figure 4 illustrate only part of the difficulty. One also must use the number of observations as a funtion of velocity to find the Weibull coefficients [22, 39] or the coefficients for an equivalent fit to the data for each compass direction. If, as is frequently asked, one must also find the seasonal characteristics of the wind, that means that there will only be an average of 1/64 of the total observations for each direction for each season. That is, for all but the 1945-1965 data, there would be less than 1000 observations. In fact, even for the 1945-1965 data there were less than 1000 observations for two season directions.

A further complication in the process of deriving the Weibull coefficients from the data occurred recently at WBF and illustrates how sensitive the final results are to small changes in the way the coefficients are derived. At WBF the surface data from Logan Airport for the years 1945-1965 is used to obtain the necessary Weibull coefficients. That data is used partly because of the large data base and partly because it includes the typical spring and summer sea breezes which would not be included in the winds aloft data (such sea breezes usually occur under a west or southwest wind aloft). Further because it is the 1 or 2 percent occurrence velocity that is of interest, the fit is made best in the probability range 0.05 to 2.00 percent. The data was first used in a program which only required annual results, and the data was reduced to find annual Weibull coefficients. In a following study both seasonal and annual results were required, so the data was reexamined to find seasonal Weibull coefficients. However, when a check was made to determine if the sum of the probabilities of a given wind velocity occurring for the four seasons added up to the annual probability, the two results were not even close. While it is true, due to the nature of the Weibull fit there is no reason to expect such an addition to result in an exact comparison, a better comparison than was found seemed possible. The data was then reanalyzed to obtain a different set of Weibull coefficients for both annual and seasonal use, for which the seasonal probabilities would add up to close to the annual probability for any wind velocity and direction. When those new and "better" Weibull coefficients were used to rereduce the wind tunnel data from the original study, it was found that the predictions for the one percent occurrence average velocity were decreased by an average of about one mile per hour. Thus even small differences in the way a given set of data is reduced can make significant differences in the final results.

Based on the above considerations it is suggested that in the future the BRA provide to the developer, and thus the wind

tunnel operator, the set of Weibull coefficients or the equivalent to be used in each study. Otherwise, it is very unlikely that the predicted velocities from two different tunnels will be equal for a given station under the same conditions.

VIII CRITERIA FOR PEDESTRIAN LEVEL WINDS

Many authors have attempted to define criteria for pedestrian level winds [1, 3, 6, 8, 14, 25, 26, 27, 29, 30, 33, and 36]. The task is made especially difficult because it is complex and the results are subjective. Further, to be meaningful the result must be expressed in probabilistic form.

One of the first attempts to define a criteria for wind was made by Admiral Beaufort in 1806. His were absolute criteria designed to allow a sailor to tell the difference between light breezes, gales, etc. It is still in use today. Penwarden [33] has reinterpreted the Beaufort Scale for pedestrian level winds (see Table 1). However, one must be careful using Table 1, since the original Beaufort scale was apparently based on average winds, and the values given by Penwarden are for some sort of average gust similar to the effective gust defined below.

What is significant about his scale is that at or above Beaufort 9 (47-55mph) a number of authors [24, 29, and 30] have noted people have great difficulty in walking and some have been hurt. Thus it is now generally agreed [3, 6, 14, 20, 24, 26, 27, 28, 29, 30, 33, 35, and 39] that wind speeds of Beaufort 9 or greater are dangerous and unacceptable.

Another aspect of the problem is what kinds of winds are annoying, and/or affect a person. The two most significant works in this area are by Hunt et al [24] and Murakami et al [30]. Both conclude that gusts shorter than 2-3 seconds do not seriously affect people. It is for that reason that the use of a low pass filter is felt necessary in all tests. Such a filter can be used to eliminate all gusts shorter than the equivalent of 2-3 seconds full scale (see Section V).

Both the Beaufort 9 wind velocity and 2-3 second gust duration are absolute criteria. Clearly, in a major storm it would not be surprising to encounter Beaufort 9. On the other hand, it is reasonable not to expect Beaufort 9 very often. The question how often it is acceptable, leads to using a probabilistic approach.

In 1978, Melbourne [27] reviewed the literature to find comprehensive probabilistic criteria for hourly average pedestrian level winds that would be applicable to different types of pedestrian activities as well as cover the safety aspects. He found and included data from Canada [6], England [24, 26, and 34], and Australia [28]. When assembled on a single plot, all the criteria proved to be similar. The results of that study are summarized in Figure 5. The results of Radovsky and Durgin [36] and Cohen et al [3] from the USA

have also been included. The vertical scale is the average hourly velocity in miles per hour and the horizontal scale is the probability based on hours of that average velocity occurring. Five criteria are given and labeled. They are "unacceptable and dangerous", "uncomfortable for walking", "acceptable for walking", "acceptable for short periods of standing", and "acceptable for long periods of standing or sitting". The estimates of occurrence in weeks, months, and years are due to Davenport [6] and allows for the fact that several occurrences may occur during one storm. Melbourne's criteria for hourly average velocities have been in use at WBF for about six years.

Originally Melbourne set up his criteria based on the peak two second gust occurring once in 1000 hours, or 3-4 times during one storm each year occurring during daylight hours. He chose to use Beaufort 9 (23 m/s (51 mph)) for the dangerous, unacceptable peak gust at P(U>Up)=0.001 because, as noted above, it is generally accepted that a gust of that strength is likely to knock a person down. To obtain the fit with the average data from other investigators shown in Figure 5, he divided his peak velocities by 1.5.

Pedestrian level winds tend to be unsteady, and thus when measuring them one usually determines the average, the root mean square variation about the average (rms), and the peak velocity. A problem arises in how to define what is sensed as too windy, because sometimes it is the average, sometimes the rms (i.e. gustiness), and sometimes the peak gust or a combination that makes a place seem windy. To overcome this difficulty, a number of authors have defined an effective gust equal to the average plus a constant (g) times the rms. Values of the constant g from 1.0 to 3.5 have been proposed, 1.5-1.75 being the most common. The guideline maximum effective gust velocity of 31 mph used by the Boston Redevelopment Authority is apparently based on using a value of 1.5 [3, 20, and 35].

The basis for the use of the constant g is that, if the distribution of gusts over an hour were Gaussian with respect to amplitude, the effective gust then would have a fixed probability of occurring in that hour. Unfortunately, the assumption that the distribution of gusts is Gaussian, while true on the average, is not true for individual stations and wind directions. If it were, the gust factors measured in the wind tunnel and/or full scale would be constant (3.5-4.0), and not vary from 2 to 10 as they typically do.

To obtain a probabilistic description of the pedestrian level wind at any station, the appropriate velocity measured in the wind tunnel must be combined with a statistical description of the wind climate in the manner described in Appendix II. Melbourne's report and experience at the WBF indicate that, on the average, the predicted peak two second gust velocities,

found as indicated above, are a little less than two times the predicted hourly average velocities. Further, if one uses g = 1.50 the predicted effective gust velocities will be about 1.43 times the predicted average velocities. Thus, one can apply Melbourne's criteria to all three types of velocities. This has been done and the results are given in graphical form in Figures 6a, 6b, and 6c. At WBF the criteria for each type of velocity is applied to each station and the catergory of the station defined as the most windy as determined for all three comparisons. The idea of appling Melbourne's criteria to each type of velocity (average, effective gust, and peak) is probably not new, but the idea of using all three together, as has been done at WBF for the last six months, is. When the criteria as given in Figures 6a, b, and c are applied to the one percent average, effective gust, and peak gust velocities defined in this report, the criteria can be stated as follows:

MELBOURNE'S CRITERIA FOR AVERAGE, EFFECTIVE GUST, AND PEAK GUST VELOCITIES

CATEGORY	VELOCITY (mph) HOURLY AVERAGE	EFFECTIVE GUST	PEAK GUST
1 UNACCEPTABLE-DANGEROUS	$27 \le U_{av}$	$39 \le U_{ep}$	$55 \le U_{pk}$
2 UNCOMFORTABLE FOR WALKING	$19 \le U_{av} < 27$	$27 \le U_{ep} < 39$	$37 \le U_{pk} < 55$
3 ACCEPTABLE FOR WALKING	$15 \le U_{av} < 19$	$21 \le U_{ep} < 27$	$30 \le U_{pk} < 37$
4 STATIONARY SHORT EXPOSURE	$12 \le U_{av} < 15$	$16 \le U_{ep} < 21$	$23 \le U_{pk} < 30$
5 STATIONARY LONG EXPOSURE	$U_{av} < 12$	$U_{ep} < 16$	$U_{pk} < 23$

The dotted lines in Figures 6a, b, and c show the estimated conditions at 4.5 feet at Logan Airport in Boston for the three velocities. The BRA effective gust guideline velocity at 31 mph 1% of the time has been converted to apply to the average and peak velocities using the same relationships as used above to convert Melbourne's criteria. The result is shown in each figure (star in a circle). Note that these values lie above Melbourne's uncomfortable for walking criteria, but well below the unacceptable dangerous criteria. This is a quite acceptable choice, since Boston is in a relatively windy area.

At WBF, only the average, effective gust, and peak gust that occurs once in 50 or 100 hours are used. However, each value listed really defines a complete curve like those in Figures 6a, b, and c passing through that point ($P(U>U_p)=0.01$). Because of the way the Weibull coefficients are derived at WBF,

the accuracy of the plot will be best in 0.05 t0 2.0 percent probability range.

Finally, in evaluating a station to find its Melbourne criteria, it is assumed that the category into which a station falls is the most windy (lowest of 1-5) of the three above (average, effective peak, and peak) that it falls into. In general, this will lead to some stations falling into a windier category than if only one criteria were used. In this way windiness due to average, rms, and peak winds can all be accounted for. Further. experience at WBWT has shown that 90 t0 95 % of the time it is the the average velocity that determines the category of any station that falls in category 1 or 2 or above the BRA criterian. Thus, it is possible in certain cases for a station evaluated using only the current BRA effective gust criterian to pass the BRA criterian, but not pass the Melbourne's criteria. The implication here is that, as used today, the BRA criterian is not necessarily as much above Melboune's criteria as one would gather from Figures 6a, b, and c.

As pointed out above, this is a relatively new innovation on the use of Melbourne's criteria. The particular definition of the effective gust used was chosen because it was believed to conform with that defined by the BRA. That definition is a very reasonable one when only the effective gust is being used to estimate the windiness of a station. However, because the use of g = 1.5 means that on average the rms only contributes about 30 percent to the total effective gust velocity, it may not be the optimum value of g, when the effective gust is used as it is here.

Finally, something more needs to be said with regard to the way Melbourne's criteria, which were developed for average winds, have been modified to apply to effective and peak gusts. These modified criteria were obtained by multiplying the velocities from the average criteria by 1.43 and 2.00 respectively. In turn these factors were developed by assuming an rms of about 30 percent and g = 1.5 and 3.5 for the effective and peak gusts respectively. The choices made above were the result of a careful survey of the literature, but it is of interest to examine the validity of the values used.

Originally most investigators only used the average winds to determine the windiness of a station, because, while it was recognized that gustiness and peak gusts could play a part in making a station windy, it was felt it was the average wind that made most stations windy. Further, the observation was frequently made that at the windiest stations the relative turbulence (rms) was reduced. The fact that Melbourne developed his criteria for average winds bears witness to that fact. The use of the effective gust came as a result of the realization that gustiness does play a part in the percieved

windiness of some stations. The general agreement in the literature on the use of values of g of 1.5 to 2.0 for computing the effective gusts (for peak gusts a value of 3.5 would be more reasonable and a value of 1.5 is used by the BRA) shows again the general agreement that the average must be heavily weighted in effective gust criteria.

The point of the above is that from the various considerations discussed, one would expect that when criteria are set up for the average, effective gust, and peak gust and used in the way they are at WBF one would expect that for the windiest stations (those falling in categories 1 or 2) the average velocity would determine the windiness of a station most of the time, the effective gust be the next most often, and the peak gust the least often. To date a total of 774 station seasons have been examined at WBF. Of these 132 were found to be in Melbourne category 1 or 2 and the average velocity determines the Melbourne category for 126, the effective peak for 6, and the peak gust for none. This distribution seems quite reasonable in terms of the observations made above and thus confirms that the methods and criteria are working in the way experience would suggest they should. The implication of the above observations is that for those stations falling in categories 4 and 5 the opposite would be true (i.e. the peak velocity criteria would determine the category the most often). However, it must be pointed out that much more wind tunnel experience and many on site observations will be needed to further refine the use of Melbourne's criteria in this way and the exact relationships between the criteria for average, effective gusts, and peak gusts.

IX SOME POSSIBLE METHODS OF CHECKING THE VALIDITY OF THE TUNNEL RESULTS

In each of the previous sections of this report ways have been suggested of ensuring that the results from any two wind tunnels are comparable, and some possible ways of verifying that results are indicative of what will happen full scale. A summary of what was said concerning the wind tunnel tests follows:

1) Some range of values must be specified for the approach boundary layer flow. For instance, an equivalent full scale gradient height of between 1200 and 1300 ft, a power law exponent of between 0.22 and 0.28, a turbulence level of at least 11 percent of gradient velocity, and a match within a factor of two of the integral scale.

2) The model scale should be such that it matches the simulated earth's boundary layer and that all buildings within 1600 feet of the sight are modeled. All buildings taller than 25 stories and within 2400 feet of the proposed building should be placed at the appropriate location upstream of the proposed building during the test. Photographs of the area model should be required in the written report.

3) As Melbourne [28] so appropriately points out pedestrian level wind studies should be started during early stages when the massing of the buildings is being planned. At a minimum the city should insist that some flow visualization studies be done at that time. Preferably such studies should be of the erosion type with a set of pictures at say 0, 15, 20, 25, and 30 mph for 12 directions (N, NE, E, SE, S, SSW, SW, WSW, W, WNW, NW, and NNW; For Boston this set of directions makes the set of pictures for each direction roughly equally important). These sets of pictures would serve two purposes: they would allow both the BRA and the developer to crudely assess the effect of the new building on the local wind environment; and would give the BRA and developer the kind of evidence needed to intelligently pick the stations for the more quantitative hot wire study.

4) The BRA should consider scattering some fixed stations about the city placed such that at least five will fall within any 1600 foot radius circle. Then a quantitative wind tunnel study should consist of at least 20 stations about or near the proposed building plus at least five of the standard fixed stations. It is assumed that all tests will include comparisons at all stations with and without the new building in place.

5) The data at each station must be taken with a device that is capable of measuring the dynamic variations in velocity at the equivalent of the height of a person's chest (4.5-5.0 ft). Sampling time should be for about (166000/(m x Vgr)) sec.; where m is the scale ratio (300-600) and Vgr the gradient velocity in the wind tunnel in mph (typically 30 mph).

This is the equivalent of one hour full scale for a one percent wind at gradient height of 45 mph (the approximate value for Boston). The peak velocity used should be that measured during that sample time, or the expected one for that time period as estimated from the data using an extreme value analysis as described in Appendix II. The measuring device used to measure the ground winds should have a flat frequency response from dc. to a cut off frequency of ((m x Vgr)/720) hz. This limits the measured data to the 2-3 second or longer gusts and is very important if direct comparisons between wind tunnels is to be expected, since this filtering affects both the rms and peak data.

6) The BRA must consider supplying the description of the wind climate to be used. Obviously the best data available at the time should be used. The correctness of the choice will not affect the comparisons between data from different tunnels, but will be important if an attempt should be made to verify the wind tunnel results by obtaining full scale data at some of the reference stations.

7) The criterian currently in use in Boston is very reasonable considering when it was developed, but it does not adequately account for the average winds and peak gusts that are possible as noted in Section VIII. Further, it does not provide any criteria in terms of the different possible pedestrian activities. Clearly, something like Melbourne's criteria as described in Section VII is needed. The problem remains that any such criteria is subjective and may need to be modified depending on the city involved. For instance, a 16 mph wind in Orlando Florida is twice its average wind and would seem very windy there, whereas in Boston its only 1.4 times the average wind.

The major thrust of this report has been to develop some guidelines that would ensure that the data from any two wind tunnels are directly comparable. While there is much evidence that the overall methodology is valid, the only really comprehensive study to date was carried out in Japan by Murakami et al [30, 31]. In the Boston area there was the study by Cohen et al [3], but that was far less extensive and did not really address the issue of the relative accuracy of the wind tunnel data and its use in predicting the occurrence of winds.

It would seem that besides establishing ground rules for wind tunnel testing and data reduction, the BRA also needs a check on the validity of the categories of occurrence of the wind for different pedestrian uses as suggested by Melbourne, and an assessment of the actual accuracy of the wind tunnel based predictions.

Both of the above objectives could be accomplished by selecting the proposed reference stations to be used in the wind tunnel to cover all of Melbourne's categories and then

arranging to obtain long term on-site data at a selected group of the stations. Such a program would involve installing an anemometer at each selected station and recording the wind velocity for a period of about one year. Simultaneously, surveys of what people do and how they feel about each station would be needed. The author believes that if most of the proposed requirements for a wind tunnel test are implemented, the suggested comparison between wind tunnel and on-site data would be the most controlled comparison carried out to date. Not only would such a study prove the validity of the use of wind tunnels, it would show that with proper controls one could achieve results from different wind tunnels that are directly comparable.

X CONCLUSIONS

All the facets of a typical study of pedestrian level winds in a wind tunnel have been reviewed and suggestions made on specifications that might be made by the BRA to make the results from several wind tunnels more comparable than they are today. Included in this review is a suggested modification of Melbourne's criteria for pedestrian level winds that makes it possible to explicitly include the effects of average wind, effective gusts, and peak gusts in the criteria. Finally a program of on-site measurements is suggested that would allow an evaluation of the accuracy of the suggested wind tunnel techniques as well as the categories for different pedestrian activities as given in Melbourne's criteria for the city of Boston.

It should be borne in mind that this report is intended as a preliminary study based primarily on the author's experience. The literature cited is therefore limited. A more complete literature survey is advisable before implimenting many of the suggested procedures other than on a temporary basis.

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APPENDIX I

CALIBRATION OF THE SIMULATED EARTH'S BOUNDARY LAYER

A1.1 INTRODUCTION

Proper wind tunnel simulation of the earth's atmospheric boundary layer requires careful consideration of the significant scaling relationships. Three parameters in wind tunnel to full scale simulation are: (1) the gradient of the average velocity,(2) longitudinal root-mean-squared (RMS) turbulence fluctuation about the average, and (3) the power spectrum of the longitudinal velocity component. Scaling on the basis of these parameters represents state-of-the-art methods in wind tunnel testing of ground structures. Each of these parameters and a "similarity relation" for sampling times are discussed in some detail below.

A1.2 VELOCITY GRADIENT SIMULATION

The gradient of the average velocity, or variation of the average velocity with height, can be simulated readily (Epstein [19]). Davenport [7] states that while other more sophisticated approximations exist to the vertical velocity gradient of the earth's boundary layer, the overall accuracy is not significantly better than the simple approximation:

$$U/Ug = (h/hg)^{\alpha} \qquad \text{(eq 1A.1)}$$

where:

U = average wind velocity at height h

Ug = average wind velocity at gradient height hg

α = power law constant, typically varies from 0.14 to 0.45

Davenport [5,7] and others show that hg and vary approximately with the terrain, as given in the table below. These parameters and their appropriate terrain are depicted in Figure A1.

GRADIENT HEIGHT AND EXPONENT AS FUNCTION OF TERRAIN

TERRAIN	GRADIENT HEIGHT	EXPONENT
URBAN	1700	0.40
SUBURBAN	1300	0.28
OPEN	900	0.16

A typical boundary layer used at WBF for a Boston study is shown in Figure 3a. and hg had values equivalent to 0.25 and 1300 feet full scale. Most sites in Boston are surrounded by the city on all sides. With an area of at least 2000 feet radius of the city modeled in the wind tunnel both upstream or dowstream of it, it is felt that the flow at the site is

dominated by the presence of the city model. Thus the typical values found for and gradient height are considered reasonable. It must be remembered that the values for α and hg presented in the table above are guidelines and are representative of the velocity gradients that Davenport[7] and others [4, 38] suggest from surveys of experimental results. These values cannot be expected to agree exactly with any site. For a review of the variations that have been found by other authors at other sites, see the article by Counihan [4]. It is for this reason that some latitude is suggested for both the exponent and boundary layer height in the text.

If the gradient height in the wind tunnel is too high or not high enough the correct velocity ratios can be calculated by dividing by the extrapolated tunnel velocity at the correct height instead of that at the top of the boundary layer without introducing significant errors. This type of correction only can be done for buildings which are less than one-half the full scale boundary layer height and if the simulated boundary layer is at least twice the height of the building.

A1.3 LONGITUDINAL TURBULENCE INTENSITY

Longitudinal turbulence intensity is a measure of the root-mean-squared (RMS) velocity variation about the average longtitudinal velocity (i.e a measure of the energy in the gusting part of the flow). In Figure 3b the ratio of longitudinal turbulence intensity to gradient wind velocity for a typical boundary layer used at WBF is plotted versus height in the wind tunnel and compared with full scale wind data. The wind tunnel values are compared with strong wind data from Brookhaven, NY, USA, and Sale, Australia, as prsented in Campbell and Standen [2].

Brookhaven is considered typical of suburban areas and so Campbell and Standen [2] have assumed the exponent α = 0.28 and height hg = 1300 feet. Sale, Australia is considered to represent open terrain and has been assigned α = 0.16 and hg = 900 feet. These values appear to have been selected directly from Davenport's results, which were given above in section A1.2. In a later publication, Counihan [3] who reviewed full scale data for many sites, presents values of α = 0.21 to 0.33 for Brookhaven and α = 0.16 to 0.176 for Sale. These have been compiled from various authors published since 1955. The scatter in the values is probably reasonable, since it is unlikely that any of the data was taken in truly adiabatic conditions. Thus a comparison of measured wind tunnel turbulence intensity to atmospheric conditions must be interpreted for general, not exact, agreement.

For a typical site in Boston, the turbulence intensity in the wind tunnel should fall within the scatter of the Brookhaven and Sale data (i.e. > 0.11 and < 0.15).

A1.4 POWER SPECTRAL DENSITY

The power spectral density is a measure of the distribution of the kinetic energy of the velocity fluctuations over the entire range of fluctuating frequencies encountered. The power spectrum of the longitudinal velocity component of the simulated flow described above is usually obtained with the aid of a computer. The wind velocity is sampled at a fixed rate (100 to 500 hz) for a specified length of time, the data is then passed the data through a fast Fourier transform to calculate the values of the power spectrum. Data is usually taken at 12 inches above the wind tunnel floor, corresponding a full scale height of one over the scale factor of the model used in the tests. A typical power spectrum obtained at WBF is shown in Figure 3c. It is the average of 32 spectra. The shape of the spectrum shown is in reasonable agreement with the empirical strong wind spectrum proposed by Davenport and Isyumov [7] and the more theoretical spectrum of Von Karman (Epstein [19]). Davenport's spectrum is defined by:

$$\frac{nS(n)}{\sigma^2} = \frac{2}{3} \frac{X^2}{(1+X^2)^{4/3}} \qquad \text{(Eq 1A.2)}$$

Von Karman's spectrum is defined by:

$$\frac{nS(n)}{\sigma^2} = \frac{2}{\pi} \frac{X_v}{(1+1.8\,X_v^{\,2})^{5/6}} \qquad \text{(Eq 1A.3)}$$

where:

X = nL/U33
Xv = 2 nlx/Ug
S(n) = power spectral density function
N, n = frequency - full scale,model
U33 = average full scale wind velocity at 33 feet above ground surface
L = 3000 feet full scale
lx = Integral scale, 400 feet full scale
σ = RMS of flunctuating wind velocity

According to Davenport [7], the power spectral density function is independent of height for much of the boundary layer height. Wind velocity is a function of height, h. To convert N/U33 full scale to n/U1 in the tunnel (U1 is the average wind velocity at 1 foot above the floor of the tunnel where the spectrum is usually measured), the following relationship is used:

$$\frac{n}{U_1} = m \left(\frac{33}{m}\right)^{\alpha} \frac{N}{U_{33}} \qquad \text{(Eq 1A.4)}$$

where m is the reciprocal of the scale factor and is the velocity gradient power law constant. For the boundary layer shown in the figure m=400 and = 0.25.

Note that proper matching of the power spectrum assures that the sizes of the gusts in the wind tunnel are appropriately scaled and distributed over the range of gust sizes.

A1.5 SIMILARITY RELATION FOR SAMPLING TIMES

A1.5.1 Introduction

In order to use the wind tunnel results with the predicted return period winds from the wind climate analysis, it is necessary to establish for the particular model scale and tunnel conditions what time in the wind tunnel constitutes the equivalent of one hour full scale. A full scale time span of one hour was chosen because of its location in the meteorological spectral gap, as reported by Van der Hoven [40].

For an average or RMS wind velocity, the one hour time span is not critical. The requirement is only a sufficient time to obtain the average and the RMS variation about the average. When measuring peak winds, an increased sampling time results in increased peaks, due to the random nature of the peaks. The increases in the peaks display diminishing values as the sampling time increases without bound. Thus it is important when peaks are measured that the time relationship between model and full scale be appropriately established.

The "similarity parameter" (nondimensional time period) used for establishing the time relationship is :

$$TU/D = tu/d \qquad \text{(eq 1A.5)}$$

where:

- T, t = period of sampling time,
- U, u = average wind speed during sample,
- D, d = characteristic dimension of model or building, and Capital and lower case are for full scale and model respectively.

This "similarity parameter" should be held constant between a wind tunnel model and a full scale situation.

A1.5.2 Ground Winds Sampling Times

In a typical hot wire study the gradient wind is kept at about 30 mph. The 100 hour return period gradient average hourly wind speed in Boston is 44 mph. Because the ratio of pedestrian level wind speed to gradient wind speed is the same for both the wind tunnel and full scale, the ratio of the pedestrian level wind speeds will be the same as the ratio of gradient wind speeds. Thus an estimate of the required sampling time for the model can be found from the previously mentioned nondimensional time period.

$D/d = m$, $u = 30$ mph, $U = 44$ mph, $T = 3600$ sec,
Thus $t = 5300/m$
which leads to $t = 13.2$ sec for a 1-400 scale model

Murakami et al [30] and others [24] have shown that only gusts lasting longer than two to three seconds seriously affect people. Thus it is important to only measure those gusts lasting longer than the equivalent of two seconds full scale. Using the same reasoning and values as above except that $T = 2$ sec it is found that only gusts lasting longer than about $3/m$ seconds in the wind tunnel should be measured. Thus typically a 0.005 second resistance-capacitive filter is used to filter the output of the hot wires at WBF.

APPENDIX II

REDUCTION OF DATA AT WBF

A2.1 WIND TUNNEL HOT WIRE DATA

Two hot wires are used at a time to measure the wind velocity at each of two stations at WBF. The data from each hot wire is sampled at about five times the reciprocal of the filter time constant (in this case about 1.7m hz) to obtain 512 readings of the voltage from each hot wire. Calibration data obtained just prior to each data set is then applied to each reading and the average (Vav), root mean square variation about the average (Vrms), and the peak (Vpk) velocities found for each set of readings. Each set of 512 readings from a hot wire is one group of readings. Typically enough groups are read for each station at each direction so that the total sample is for the equivalent of one hour full scale (about 20). The 20 or so average, and rms velocities, are then combined to find the overall average (Vav) and rms (Vrms) for the entire sampling period.

A Type I extreme value analysis can be performed on the 20 peaks (one from each the 20 groups of data) from each station for each direction to obtain a better estimate of the expected peak for the 5300/m second sample than the single measured peak (see references [9] and [22]). It is this peak velocity which is usually used at WBF for all calculations.

All data is then normalized by dividing by the average gradient velocity for all groups to obtain a value for Vav/Vgr, Vrms/Vgr, and Vpk/Vgr for each station for each wind direction. These values of Vav/Vgr, Vrms/Vgr and Vpk/Vgr are then used in conjunction with a statistical description of the Boston wind climate to calculate how often a given average velocity, effective gust, or peak gust will occur at any chosen station. This procedure is carried out for all the stations for both annual and seasonal time periods.

A2.2 THE WIND CLIMATE USED at WBF

Surface wind data was obtained for Logan Airport for the years 1945 to 1965 from the National Climatic Center in Ashville, N.C. The data consists of 24 one minute observations per day taken at hourly intervals and includes over 176000 observatioms. The data was sorted by direction (NNE, NE, -- , NNW, N) and the data as a whole as well as by direction fitted with Weibull probability distributions [14, 22, 27]. The Weibull probability distribution has the form:

$$P(U>U_p) = A_n e^{-(U_p/U_n)^{K_n}} \qquad \text{(eq 2A.1)}$$

where:

P(U>Up) is the probability of U exceeding Up.

An is the total probability of the wind coming from direction n. Direction n is the included angle between one half way towards direction n-1 and one half way towards direction n+1.

Un is a scaling velocity determined from the fit of the wind climate data to the Wiebull approximation.

Kn is an exponent determined from the fit of the the Weibull approximation to the wind climate data.

The values of An, Un, and Kn were obtained for each of the 16 compass directions used for an annual time period as well as for each season. The values obtained are given in Table A2a-e. The 17th values in the tables are for all winds. The values of Un given in the tables have been adjusted so that Up is the hourly average at gradient height in order that the Weibull fit may be applied directly to the wind tunnel data. In carrying out the above correction to Un, it is assumed that the data as taken at Logan Airport were equivalent to one hour averages. The Un was corrected to gradient height by using an average height for the data of 58 feet and assuming a power law boundary layer at the airport with a gradient height of 900 feet and an =0.16.

In making the Weibull fits to the actual data from Logan it was found that it was not possible to obtain a good fit over the entire range of velocities. Since the Weibull fit obtained was to be used to calculate the velocities that occurred 1% of the time, the best fit from about 2% to 0.05% was obtained for each season and direction. Further it was found that if one also obtained the annual Weibull constants in this way from the annual data, the sum of the probabilities from the four seasons calculated from the Weibull coefficients did not add up to the annual ones for each direction. Thus the seasonal and annual probabilities calculated from the Weibull coefficients obtained this way were not consistent.

To overcome that difficulty the probabilities from each season were calculated from the derived Weibull coefficients and added up to obtain the annual probabilities. These calculated probabilities were then used to obtain the annual Weibull coefficients for each direction for the annual winds. Finally the calculated probabilities calculated from this fit to the sum of the seasonal probabilities were compared with the results from the fit to the annual data and the annual data itself. The resulting comparison showed that the fit derived from the sum of the seasonal probabilities for each direction was nearly as good as that derived directly from the annual data. Thus the coefficients derived from the sum of the annual data is used by WBF and is what is given in Table A2-a. Note

that because of the nature of the Weibull fitting process an exact agreement between the average of the seasonal velocities and annual velocity for the same probability of occurrence is not likely, but that the sum of the calculated probabilities for a given velocity calculated from the revised coefficients result in a much better agreement than from the original coefficients.

A2.3 CALCULATING THE PREDICTED ONE PERCENT RETURN PERIOD VELOCITIES FROM THE HOT WIRE DATA

The average, rms, and peak velocity ratios and the Weibull coefficients in Table A2 are used to calculate the average, effective gust, and peak gust velocities that will be exceeded during one hour once in 100 hours at each station for annual as well as seasonal time periods. To accomplish that calculation an iteration procedure is used. First one assumes a value for the 1% average, effective gust, or peak gust velocity. Then for each of the 16 directions, one divides that velocity by Vav/Vgr Veg/Vgr or Vpk/Vgr to obtain Vgr (Veg=Vav+1.5 x Vrms). Then setting Up=Vgr in the appropriate Weibull equation for that direction, one can calculate the probability of the assumed velocity occurring for each direction. The sum of the probabilities from all directions is the total probability of that assumed velocity occurring. The assumed velocity (average, effective gust, or peak gust) is then iterated until the total probability is 1%.

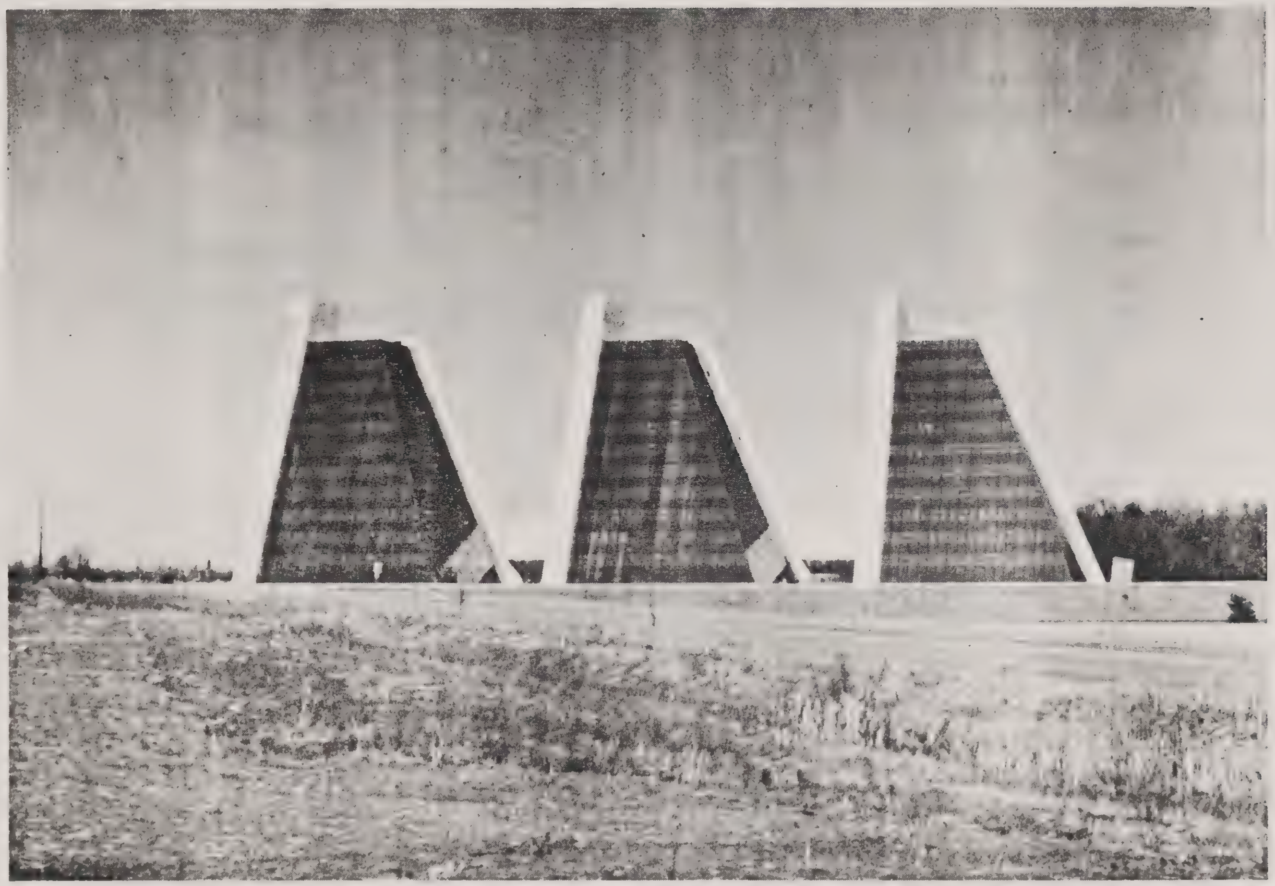
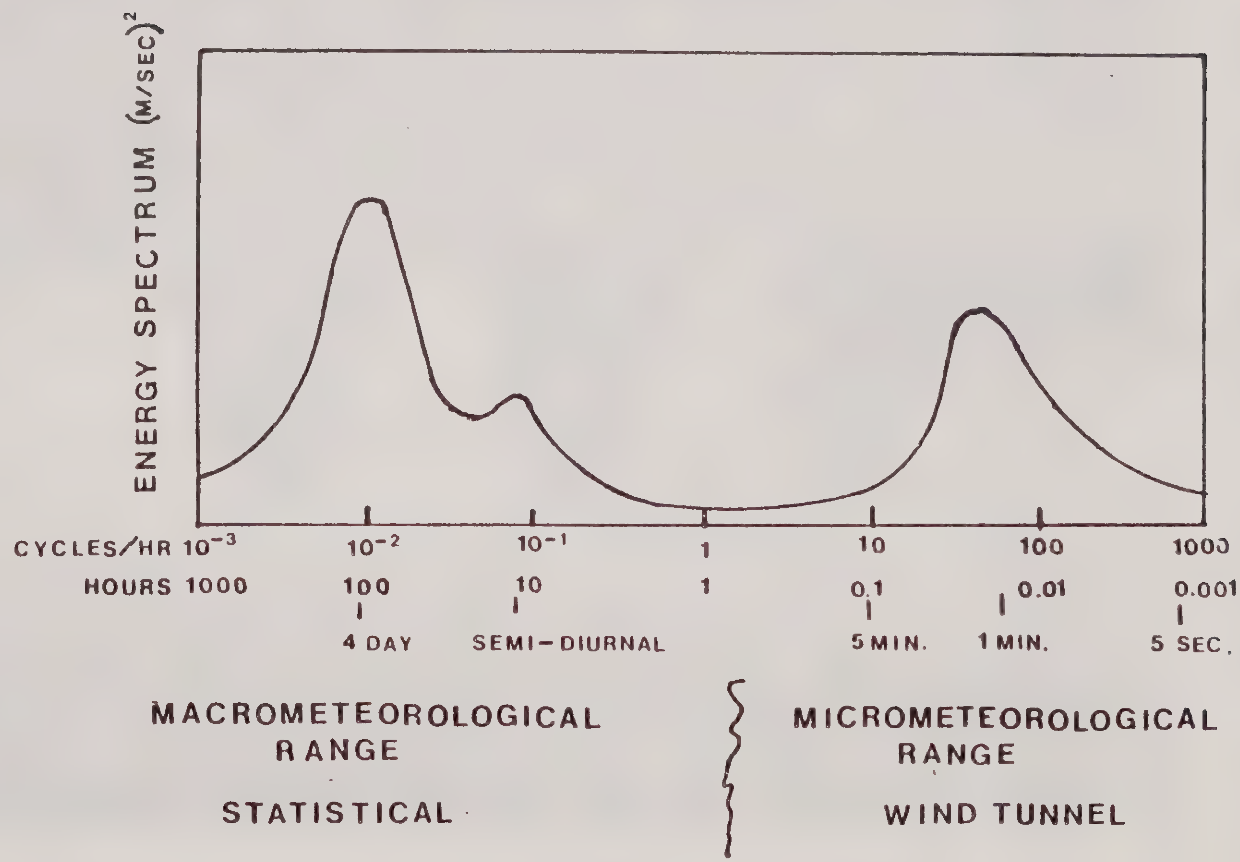


Figure 1 College Life Insurance Headquarters Building, Indianapolis, Indiana

Figure 2 THE ATMOSPHERIC SPECTRUM AFTER VAN DER HOVEN



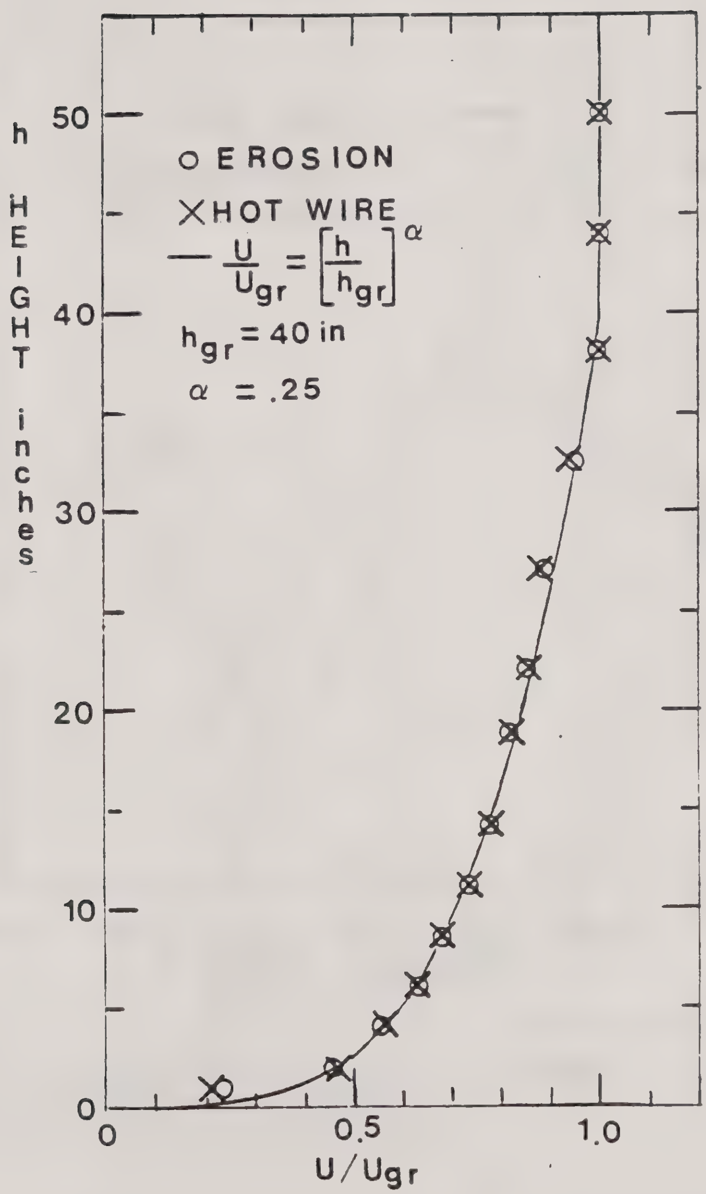


Figure 3a. Variation of average velocity with height

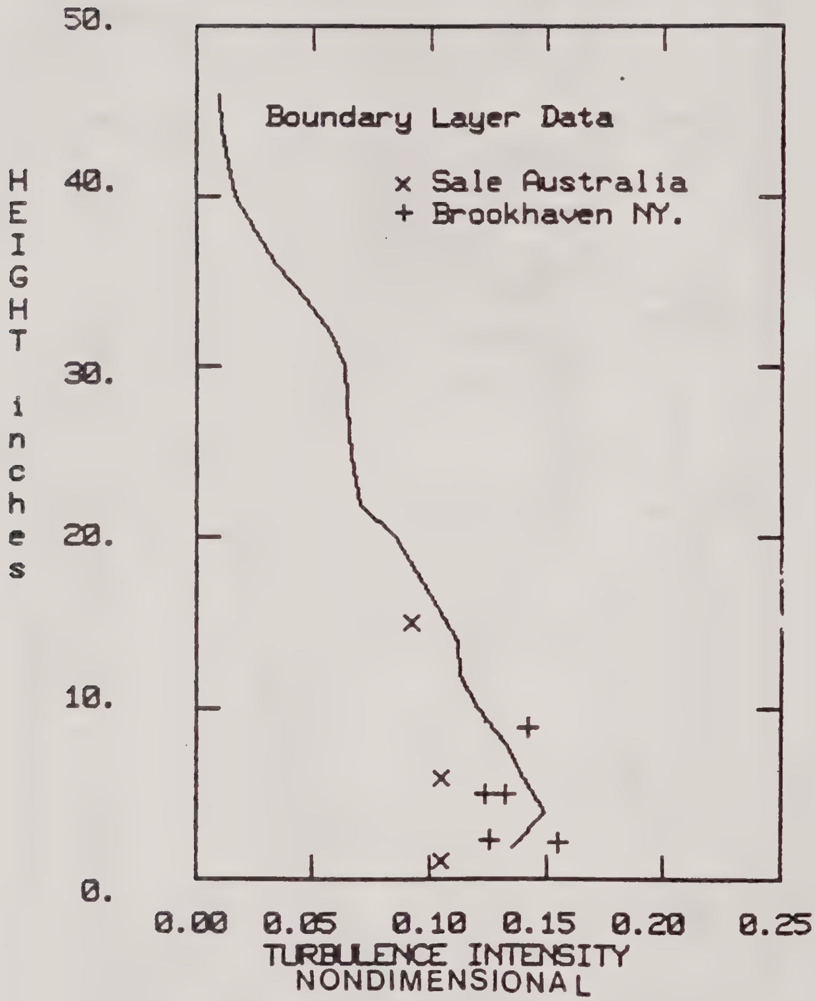


Figure 3b. Normalized turbulence intensity as a function of height-tunnel center line

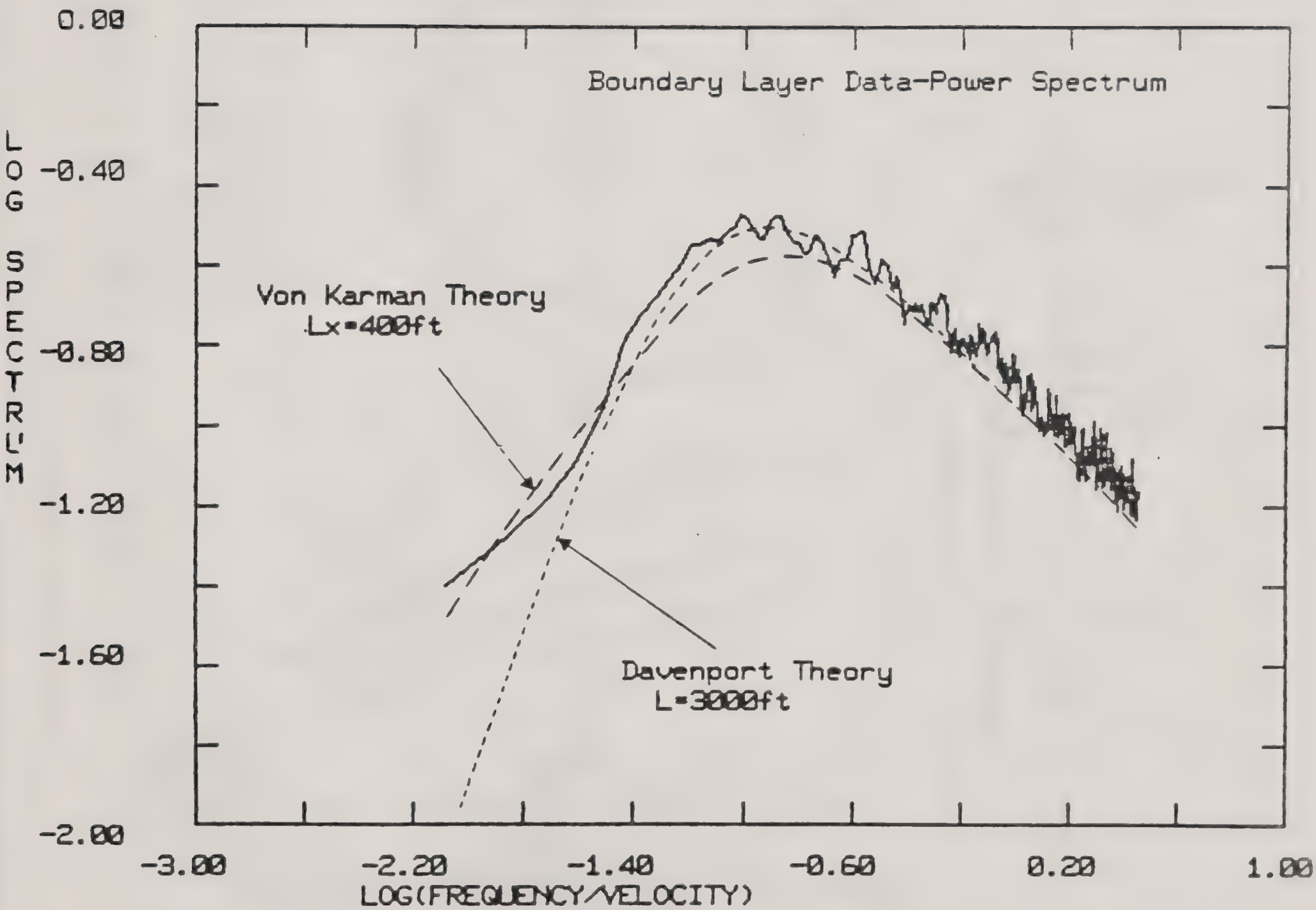
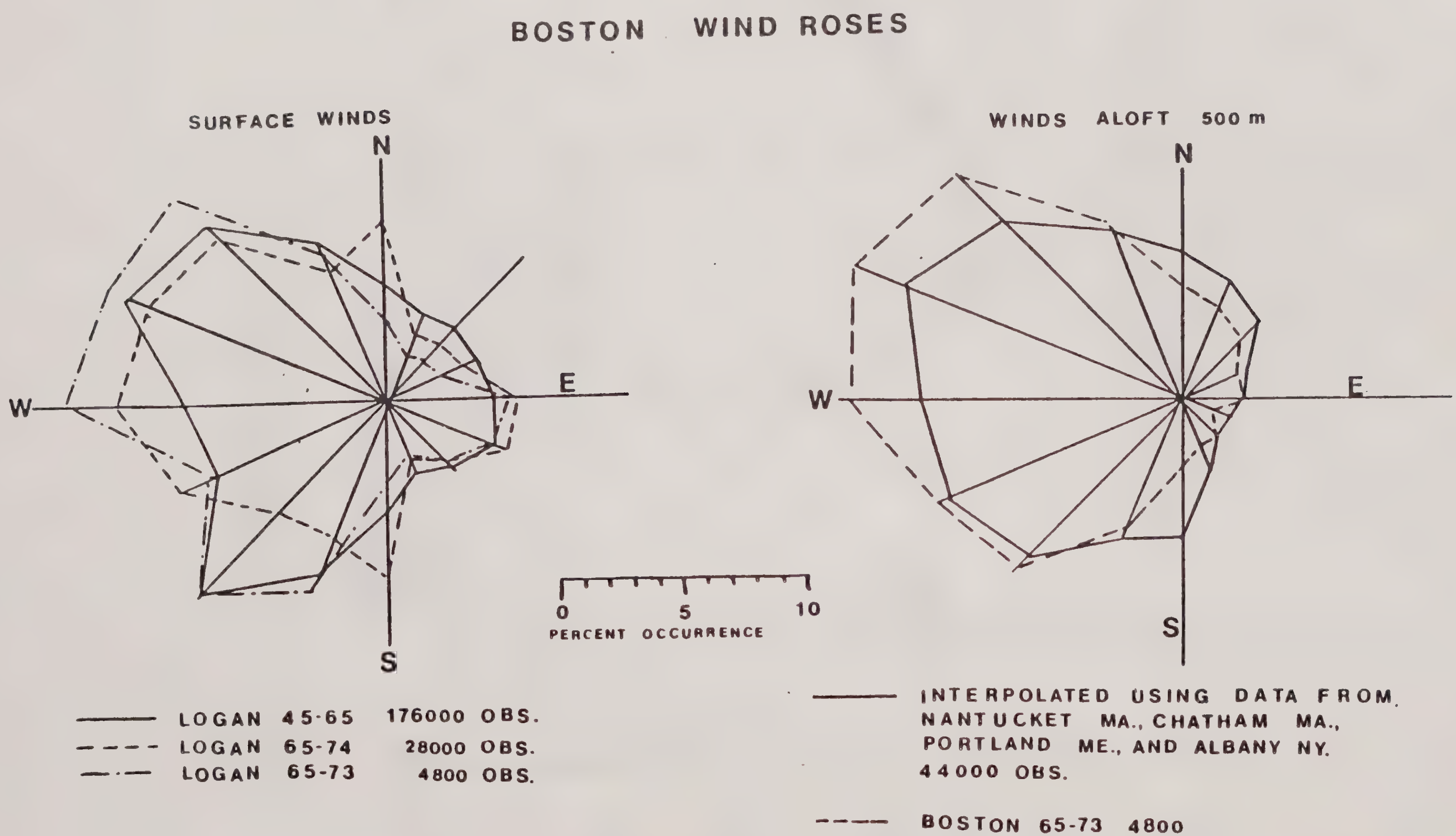


Figure 3c. Power spectrum of turbulence at one foot on tunnel center line

Figure 4 Wind Roses from Different Sources for Boston, Mass.



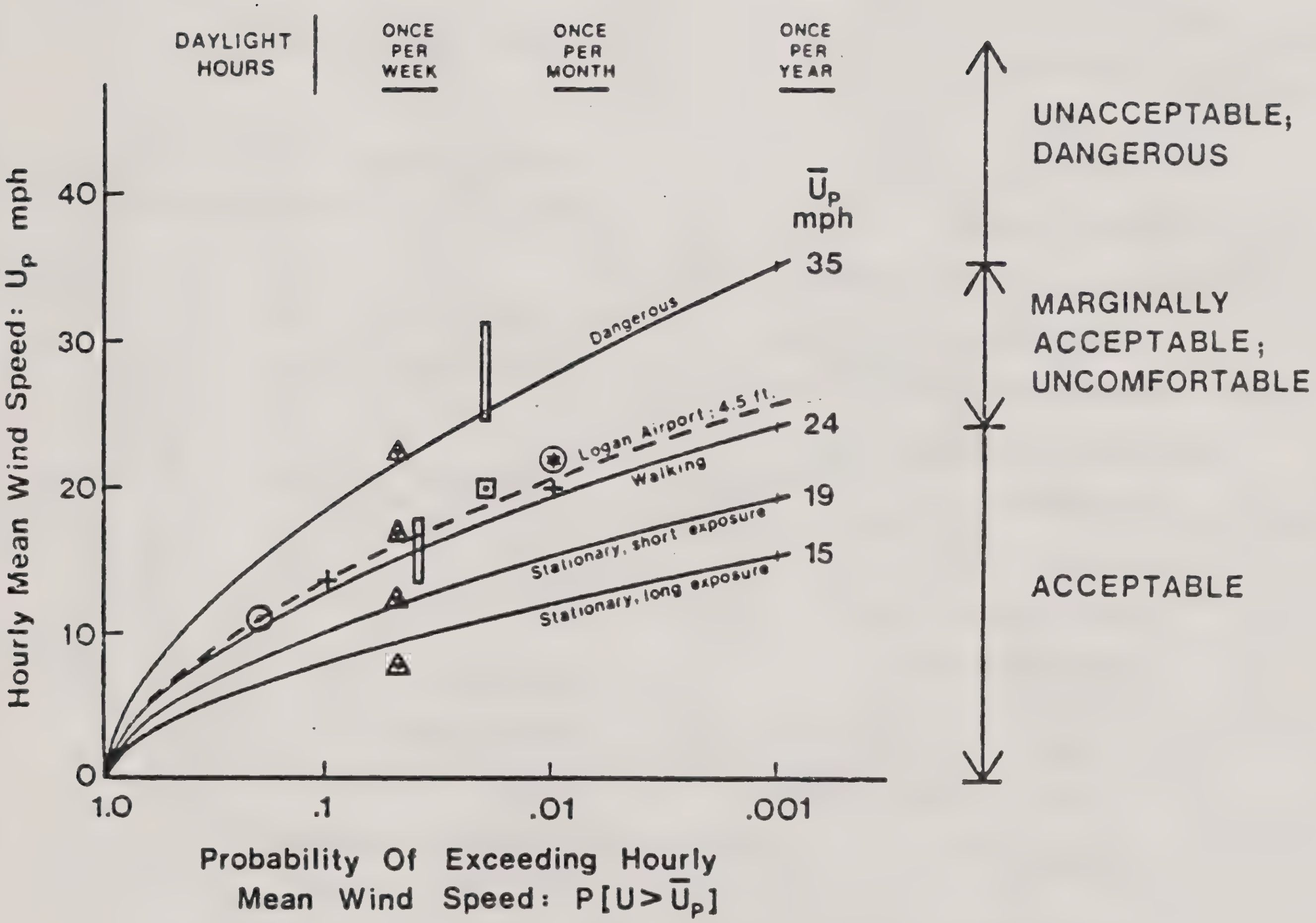


Figure 5a. Melbourne's Criteria for Average Pedestrian Level Winds - Comparison with Other Criteria

		SYMBOL
Conditions at Logan Airport		- - -
<u>Criteria</u>		
MELBOURNE [27]		———
DAVENPORT [6]		
Acceptable for:		
Walking fast	If $P[\bar{u} > 22.4] < 0.05$	△
Strolling	If $P[\bar{u} > 16.8] < 0.05$	△
Standing, Sitting Short Exposure	If $P[\bar{u} > 12.3] < 0.05$	△
Standing, Sitting Long Exposure	If $P[\bar{u} > 7.8] < 0.05$	△
PENWARDEN and WIDE [34]		
Acceptable	If $P[\bar{u} > 11.2] < 0.2$	⊙
LAWSON [26]		
Acceptable	If $P[\bar{u} > 13.4 \text{ to } 17.8] < 0.04$	═
Unacceptable	If $P[\bar{u} > 24.6 \text{ to } 31.3] < 0.02$	═
HUNT, POULTON and MUMFORD [24]		
Acceptable for Strolling	If $P[\bar{u} > 13.4] < 0.1$	+
Acceptable for Walking	If $P[\bar{u} > 20.1] < 0.01$	+
RADOVSKY and DURGIN [36]		
Acceptable	If $P[\bar{u} > 20.1] < 0.02$	⊡
COHEN et al [3]		
Unacceptable - limit for safety	If $P[\bar{u} > 20] < 0.001$	X
Acceptable for: Walking	If $P[\bar{u} > 14] < 0.05$	X
Strolling (short exposure)	If $P[\bar{u} > 8] < 0.10$	X
Sitting (long exposure)	If $P[\bar{u} > 5] < 0.20$	X
BRA Guideline*	$P[\bar{u} > 22] < 0.01$	⦿

*Converted to average hourly winds.
ALL velocities in mph

Figure 5B. Legend for Pedestrian Level Wind Criteria Graph

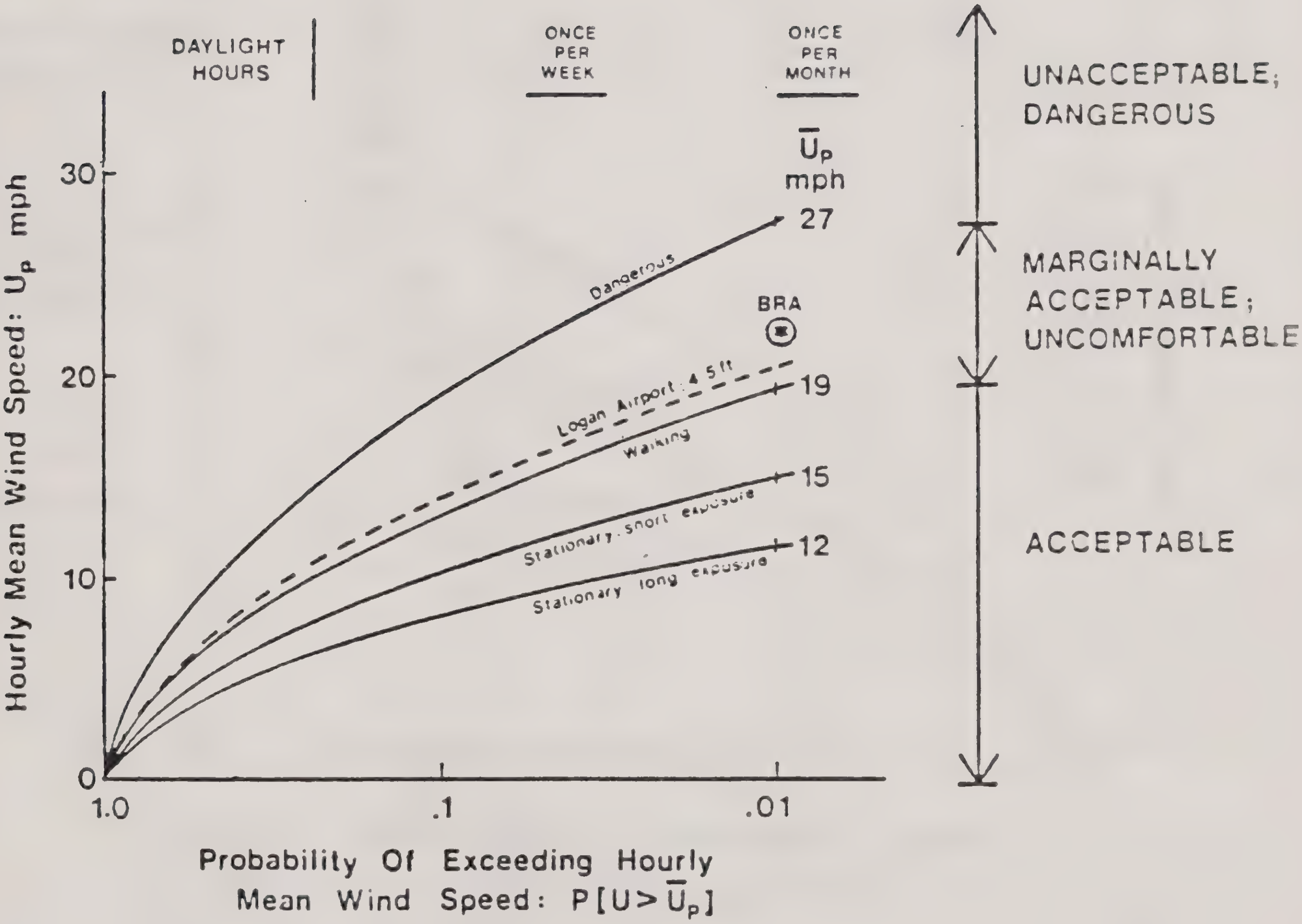


Figure 6A. Melbourne's Criteria for Average Winds

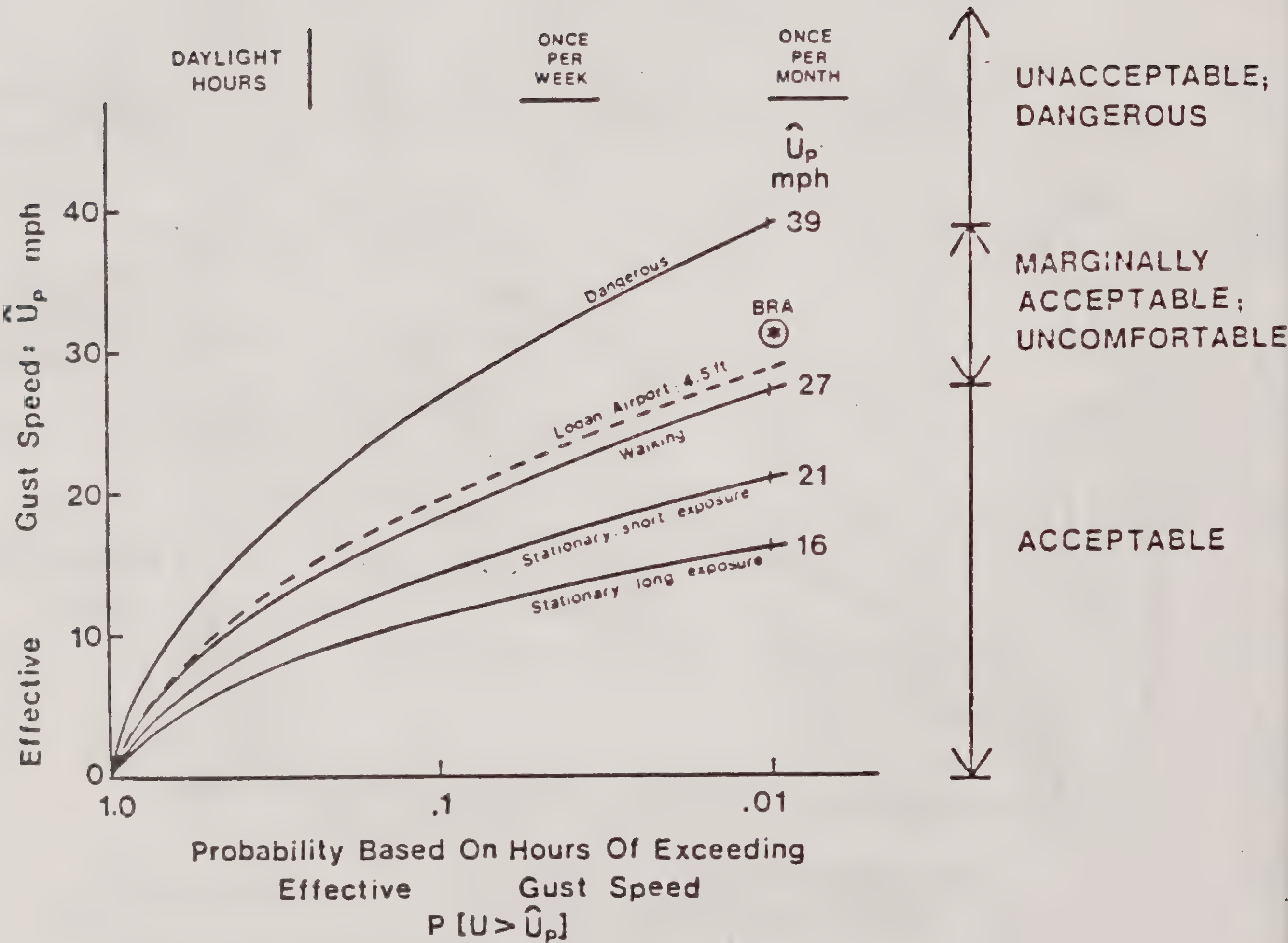


Figure 6B. Melbourne's Criteria for Effective Gusts

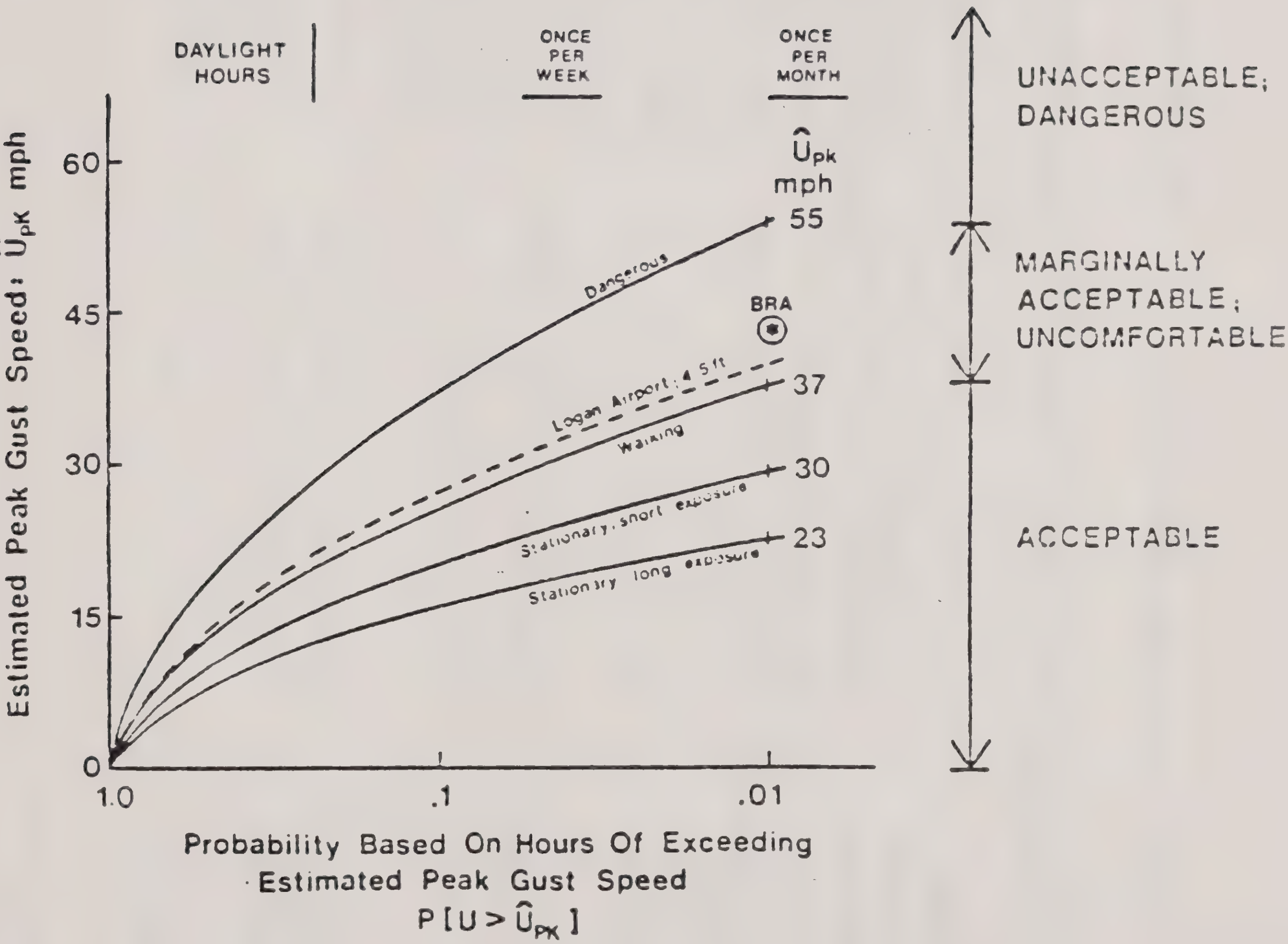


Figure 6C. Melbourne's Criteria for Peak Gusts

Table 1. Beaufort Wind Scale for Pedestrians after Penwarden

Beaufort Number	Description of Wind	Speed (m/sec)*	Speed (mph)*	Description of Wind Effects
0	Calm	Less than 0.4	Less than 0.9	No noticeable wind
1	Light airs	0.4 - 1.5	0.9 - 3.4	No noticeable wind
2	Light breeze	1.6 - 3.3	3.5 - 7.4	Wind felt on face
3	Gentle breeze	3.4 - 5.4	7.5 - 12.1	Wind extends light flag Hair is disturbed Clothing flaps
4	Moderate breeze	5.5 - 7.9	12.2 - 17.7	Wind raises dust, dry soil and loose paper Hair disarranged
5	Fresh breeze	8.0 - 10.7	17.8 - 23.9	Force of wind felt on body Drifting snow becomes airborne Limit of agreeable wind on land
6	Strong breeze	10.8 - 13.8	24.0 - 30.9	Umbrellas used with difficulty Hair blown straight Difficulty to walk steadily Wind noise on ears unpleasant Windborne snow above head height (blizzard)
7	Moderate gale	13.9 - 17.1	31.0 - 38.3	Inconvenience felt when walking
8	Fresh gale	17.2 - 20.7	38.4 - 46.3	Generally impedes progress Great difficulty with balance in gusts
9	Strong gale	20.8 - 24.4	46.4 - 54.6	People blown over by gusts

*Effective gusts

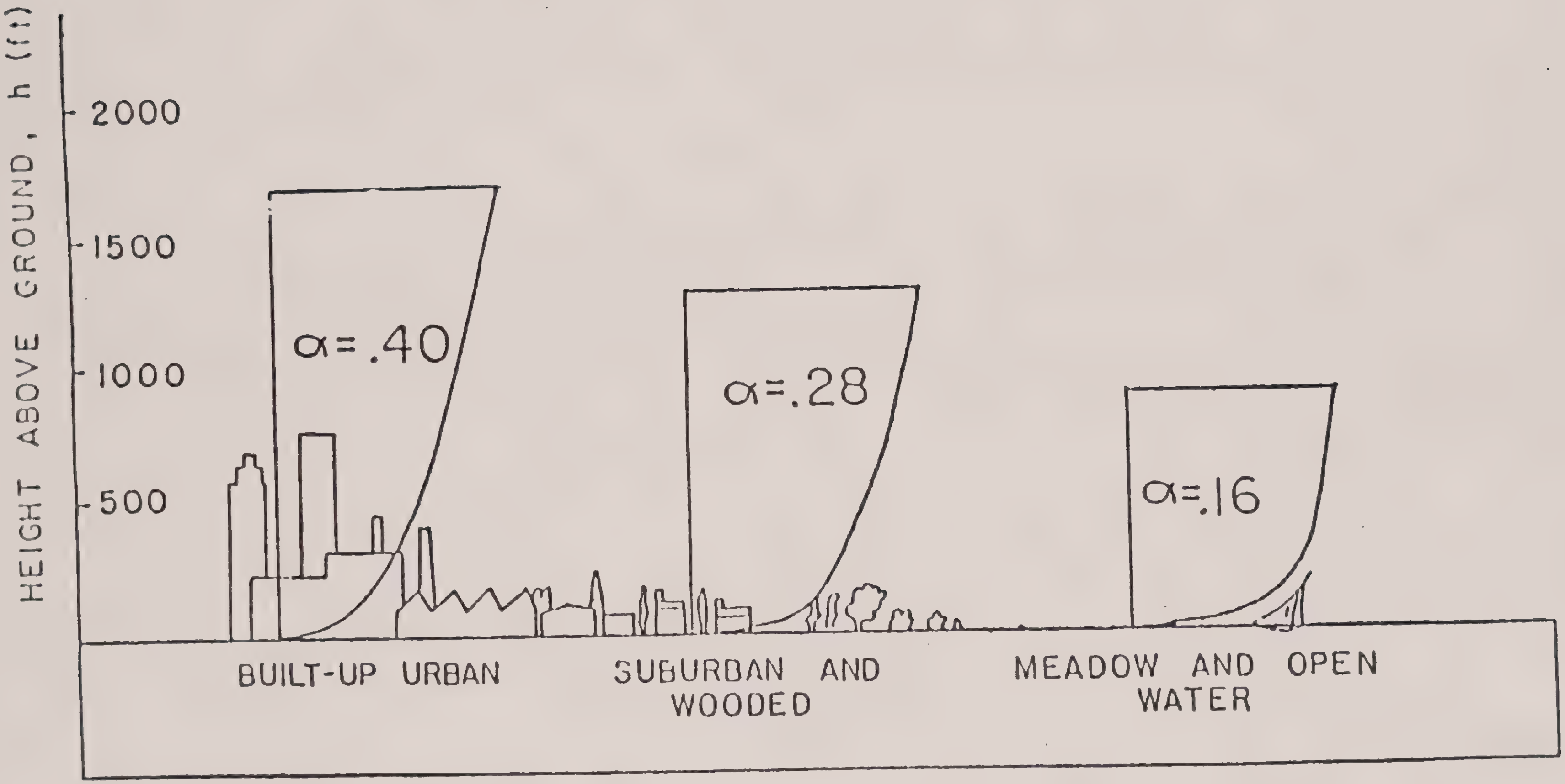


Figure A-1. Types of Earth's Boundary Layer after Davenport